

UNCLASSIFIED  
~~CONFIDENTIAL~~

Copy 6  
RM L54B08a

NACA RM L54B08a

c.2

  
NACA

# RESEARCH MEMORANDUM

CLASSIFICATION CHANGED

To UNCLASSIFIED

By authority of *Internal & Memo* Date *8-1-68*

FLIGHT TEST OF AN END-BURNING SOLID-FUEL RAM JET

*AND 8-2-68*  
By Walter A. Bartlett, Jr.

Langley Aeronautical Laboratory  
Langley Field, Va.

CLASSIFIED DOCUMENT

This material contains information affecting the National Defense of the United States within the meaning of the espionage laws, Title 18, U.S.C., Secs. 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

NATIONAL ADVISORY COMMITTEE  
FOR AERONAUTICS

WASHINGTON  
March 25, 1954

~~CONFIDENTIAL~~  
UNCLASSIFIED

UNCLASSIFIED

NASA Technical Library



3 1176 01437 1315

NACA RM L54B08a

~~CONFIDENTIAL~~

## NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

## RESEARCH MEMORANDUM

## FLIGHT TEST OF AN END-BURNING SOLID-FUEL RAM JET

By Walter A. Bartlett, Jr.

## SUMMARY

A flight investigation of a rocket-launched ram-jet engine, incorporating an end-burning solid fuel was made. During the flight the model accelerated from a Mach number of 1.9 and an altitude of 3,900 feet to a Mach number of 2.52 and an altitude of 24,750 feet in 11.7 seconds. Premature ignition of the ram jet occurred 2.95 seconds after take-off and prevented separation of the ram jet and booster at booster burnout. Booster separation did occur 3.86 seconds after take-off at a Mach number of 1.90. However, analysis of the data and observation of the high-speed flight motion pictures gave evidence that the booster adapter was still in place in the ram-jet exit nozzle until 7.50 seconds after take-off.

Maximum values of acceleration (3.2g) and air specific impulse (123 seconds) were calculated. The maximum values of net and gross thrust coefficients were 0.23 and 0.37, respectively. Ram-jet combustion was sustained to an altitude of 27,500 feet, 17.9 seconds after take-off. The model then coasted to an altitude of 47,500 feet at the time of 46 seconds, at which position it was lost by the SCR-584 radar. The fuel successfully withstood an acceleration of 25g during the boost period.

## INTRODUCTION

A solid-fuel ram jet might be used in medium thrust and medium range applications, when the high thrust of a solid-fuel rocket is not required, but where it is desirable to retain the features of simplicity and reliability inherent in a solid-fuel rocket. Although a liquid-fuel ram jet would deliver a higher specific impulse than the solid-fuel ram jet, it would perhaps be less reliable as the system does contain highly complex fuel metering devices.

The available, promising, basic data on solid metallic-type fuels, prompted the Langley Pilotless Aircraft Research Division to initiate an investigation to determine the performance of various types of solid-fuel

~~CONFIDENTIAL~~

UNCLASSIFIED

UNCLASSIFIED

CLASSIFICATION CHANGED

*file  
8-2-69**copy of Memo. and St. Mess.*

charges in both preliminary ground and flight tests. The results of the ground tests (ref. 1) indicated that the fuels had reached the stage where flight testing was deemed advisable for further evaluation. The results of the first NACA flight test of a solid-fuel ram jet, using a radial-burning-type fuel, were presented in reference 2.

The results of the first flight test of a solid-fuel ram jet, using an end-burning-type fuel, are presented in this paper. The flight test was made at the Langley Pilotless Aircraft Research Station at Wallops Island, Va.

#### SYMBOLS

p	static pressure, lb/sq in. abs
T	static temperature, °F abs
A	maximum stream tube area, sq ft
W	weight of model, lb
t	time measured from take-off, sec
S	combustion-chamber area, 0.231 sq ft
M	free-stream Mach number
q	free-stream dynamic pressure, lb/sq ft
g	acceleration of gravity, 32.2 ft/sec <sup>2</sup>
a <sub>L</sub>	absolute longitudinal acceleration, ft/sec <sup>2</sup>
C <sub>D</sub>	external drag coefficient, based on combustion-chamber area
C <sub>Tn</sub>	net thrust coefficient, $\frac{a_L W}{qS}$
C <sub>Tg</sub>	gross thrust coefficient, C <sub>Tn</sub> + C <sub>D</sub>
S <sub>a</sub>	sonic air specific impulse, $\frac{\text{lb of jet thrust}}{\text{lb of air/sec}}$
φ <sub>M</sub>	ratio of jet impulse at any station to the jet impulse at a sonic station

$T_s$  stagnation temperature,  $^{\circ}\text{F}$  abs

$H$  altitude, ft

$D$  diameter, in.

## APPARATUS AND METHODS

### Flight Model

The model, incorporating a Mach number 2.13 design conical-shock inlet diffuser, is shown as a sketch and a photograph in figures 1(a) and 1(b), respectively. The 0.093-inch wall inlet-diffuser section was attached to an 0.093-inch wall combustor shell upon which four fins, each with an area of 0.416 square foot, were mounted. Four cruciform struts of 1/8-inch thickness, with tapered leading and trailing edges, and a chord of 4 inches fastened the innerbody to the diffuser wall. An "off-the-wall clover-leaf flame holder" made of 3/8-inch mild steel enclosed in an 0.093-inch-thick Inconel shroud (fig. 1(c)) was mounted to the combustor wall with four airfoils, 1/4 inch thick, with  $1\frac{1}{4}$ -inch chord and tapered leading and trailing edges. The model was 62.95 inches in length with a combustion chamber of  $6\frac{1}{2}$  inches inside diameter.

The area ratio of the combined supersonic and subsonic diffuser was 0.884, based on the area at the entrance lip and the annular area at the end of the diffuser. The contraction and expansion area ratios of the exit nozzle are 0.853 and 0.923 when referenced to the combustion-chamber area.

The ram jet was comprised of an 0.093-inch wall spun-mild-steel diffuser and innerbody, a sheet Inconel combustor, and stainless-steel exit nozzle and fins. The empty model weight was 60.3 pounds.

The model was essentially similar to that model in which a radial-burning solid fuel was flight tested, and the results reported in reference 2.

### Fuel

The end-burning solid-fuel charge was produced by the Bureau of Mines under contract with the Bureau of Aeronautics, Navy Department. A sketch of the flight-type fuel charge is presented as figure 2, and a description of its manufacture is presented in reference 3.

The flight-test fuel charge was made up of two distinct compositions, the ingredients and percentages of each are listed in the following table:

<sup>1</sup> Composition . . . . .	MFM-124	MFM-107
Aluminum, pyrotechnic, percent (by weight) . .	15	37.5
Magnesium, 200 mesh, percent (by weight) . . .	45	37.5
Boron, amorphous, percent (by weight) . . . .	10	----
Potassium nitrate, percent (by weight) . . . .	21.4	17.9
Copper sulfate, percent (by weight) . . . . .	8.6	7.1
Percent of total weight . . . . .	45.1	54.9

<sup>1</sup>Bureau of Mines designation (see ref. 4).

The fuel charge was pressed into a liner of commercial extruded magnesium tubing of  $4\frac{1}{2}$ -inch outside diameter with a wall thickness of 0.093 inch.

The fuel charge itself, before installation of the ignitor was  $18\frac{1}{4}$ -inches long. An ignitor made up of loosely packed MFM-124 composition was installed on the downstream end of the fuel charge. Two  $\frac{1}{4}$ -delay electric squibs imbedded in the loose powder were fired for ignition. The fuel charge weight was 18.1 pounds. The liner weight was 1.6 pounds. The total loaded weight of the model was 80.0 pounds. The fuel assembly was attached to a threaded adapter with machine screws and screwed into threads in the innerbody.

#### Booster Rocket and Adapter

A Jato, 3.5-DS-5,700 rocket motor was used to accelerate the ram jet to supersonic speed. A cast-magnesium-alloy coupling fastened to the rocket motor and fitted internally in the ram-jet exit nozzle attached the booster to the ram jet. This coupling was designed to block only 10 percent of the nozzle-exit area during the boost period. Four fins, each with an area of  $1\frac{1}{4}$  square feet, were mounted at the rear end of the rocket motor to provide stability of the combination during the boost period. A photograph of the ram jet and coupled booster in place on the launcher prior to firing is shown as figure 3.

#### Measurements

The velocity of the model in flight was measured with a continuous-wave Doppler radar. The position of the model in space was determined with NACA modified SCR 584 tracking radar. The altitude of the model at any given time obtained from SCR 584 data is presented in figure 4. High-speed manually operated tracking cameras provided information on the behavior of the model in flight.

Upon completion of the flight test, a radiosonde balloon was released to obtain the pressure and temperature of the atmosphere as a function of altitude. The radiosonde balloon was tracked with NACA modified SCR 584 radar to obtain wind velocity at altitude. Values of static pressure  $p$  and static temperature  $T$  obtained from radiosonde data are presented in figure 5 as functions of altitude.

#### FLIGHT TEST

The model, launched at an elevation of  $60^\circ$ , was boosted to  $M = 1.99$ , 3.10 seconds after take-off. Premature ignition of the ram jet occurred at the time of 2.95 seconds after take-off and prevented separation of the ram jet and booster at booster burnout. Booster separation did occur at 3.86 seconds after take-off at  $M = 1.90$ . However, analysis of the data, and observation of the high-speed flight motion pictures gave evidence that the booster adapter was still in place in the ram-jet exit nozzle until the time of 7.50 seconds after take-off. After this time, the model accelerated to a maximum velocity of 2,625 feet per second ( $M = 2.52$ ) 15.5 seconds after take-off, at which time it had reached an altitude of 24,750 feet. The model then decelerated to  $M = 2.29$  at an altitude of 27,500 feet when burnout of the fuel charge occurred. The model then coasted to an altitude of 47,500 feet at the time of 46 seconds, at which position it was lost by the SCR-584 radar.

#### RESULTS AND DISCUSSION

The variation of maximum stream tube area - used in determining the weight flow of air - with free-stream Mach number is presented in figure 6. These data were determined for an inlet geometrically similar to the flight engine, both by the experimental method and the one-dimensional-flow analysis that are described in reference 5.

Prior to the flight test, preflight tests were conducted in the preflight jet of the Langley Pilotless Aircraft Research Station at Wallops Island, Va. on the high-density concentric and dual-segment fuels (Bureau of Mines designation). The fuels were tested with several types of flame holders to determine which fuel and flame-holder configuration would be flight tested. The diffuser-combustor combination used was geometrically similar to the flight-type engine.

Basic data and engine performance parameters were obtained for these tests by the methods described in references 1 and 5. Analysis of the data indicated that the concentric-type fuel charge (fig. 7), and a shrouded clover-leaf flame holder (fig. 1(c)) configuration gave the best

overall performance. The concentric fuel charge burned smoother, and with a higher combustion efficiency than did the other type. The shrouded clover-leaf flame holder promoted good combustion while preventing combustor burnout that was reported in references 1 and 2. The results of the preflight tests of the previously mentioned fuel-flame-holder configuration are presented in figure 8(a) as values of air specific impulse  $S_a$  against burning time for the free jet conditions given in the figure. Observation of figure 8(a) shows that a value of  $S_a \geq 120$  seconds was obtained at  $M = 2.1$  except between the time of 0.6 and 2.5 seconds. As it was desired that a value of  $S_a \geq 120$  seconds be the minimum acceptable for flight, the shape of the ignition end of the charge was modified to that shown in figure 2 to give a higher fuel rate than the preflight charge for the first 3 seconds of combustion. A compilation of  $\bar{S}_a$  obtained from

$$\frac{\int_0^t S_a dt}{t}$$

is presented in figure 8(b) for the various high-energy fuels and flame-holder configurations tested. The values of  $\bar{S}_a$  are plotted against fuel-air ratio which is defined as the ratio of the weight rate of fuel expenditure to the weight flow of air. Data from reference 6 are included for comparison.

The flight Mach number  $M$  of the ram jet is presented in figure 9 as a function of flight time. The velocities used to calculate  $M$  were corrected for the wind speeds at the various altitudes. Doppler velocity data were used until the time of 11.75 seconds, after which time the signal became very erratic. The SCR-584 data - with appropriate camera corrections - were used to obtain velocity between the times of 7.25 and 19 seconds. The data show a peak value of  $M = 2.52$  obtained at the time of 15.5 seconds. This can be compared to a peak value of  $M = 2.73$  obtained with the radial-burning solid-fuel ram jet reported in reference 2. The initial decrease and later slow increase in  $M$  due to improper booster separation and adapter jamming in the exit nozzle is noted. Approximately one-third of the fuel charge was expended during this period doing practically no useful work.

A time-history of the longitudinal acceleration is presented in figure 10. The values were obtained by differentiation of the velocity-time curve with an added correction for the model gravitational component. The acceleration was approximately 2g immediately after booster separation, then decreased to approximately 0.8g. A steady increase in  $a_L$  is noted

to a maximum of 3.2g at 9.3 seconds, with a constant value of approximately 3g being calculated to the time of 13.8 seconds. A maximum acceleration of 8.6g was calculated for the radial-burning solid-fuel ram jet (ref. 2).

It is pertinent to note that the fuel charge successfully withstood an acceleration of approximately 25g during the period of rocket boost.

The net thrust coefficient  $C_{T_n}$  of the ram-jet engine is presented in figure 11 as a function of Mach number. The net thrust was obtained from the longitudinal acceleration data (fig. 10) and the mass of the ram jet with appropriate corrections for changing mass with fuel consumption. The fuel expenditure was determined by assuming a constant fuel rate from ignition at 2.95 seconds to burnout at 17.80 seconds. The external drag coefficient  $C_D$  of the model (fig. 11) was estimated by using existing experimental fin drag in conjunction with theoretical friction and engine pressure drag data. The drag coefficient was used to present qualitative values of gross thrust coefficient  $C_{T_g}$  which is also presented in figure 11. Maximum values of  $C_{T_n}$  and  $C_{T_g}$  of 0.24 and 0.37 realized at  $M = 2.09$  were lower than values of 0.49 and 0.61 obtained with the radial-burning solid-fuel ram jet of reference 2.

A time-history of the air specific impulse parameter  $S_a$  delivered by the ram jet is presented in figure 12. The values of  $S_a$  at the sonic section of the exit nozzle, were obtained by adding the momentum of the air entering the ram jet to the gross thrust, and dividing this quantity by the weight flow of air and the thrust function  $\phi M$  (ref. 7). A maximum value of  $S_a = 123$  seconds was calculated from the data at the time of 14 seconds, whereas a maximum value of 148 seconds was calculated for the radial-burning solid-fuel ram jet in reference 2. It should be noted that a 10-percent error in estimated  $C_D$  reflects a maximum error of only 1 percent in  $S_a$  for these data. The calculated values of free-stream stagnation temperature  $T_s$  are also shown on figure 12.

The failure of the booster to separate properly, and the presence of at least a portion of the adapter in the exit nozzle for 3 or 4 seconds after booster separation prevented the proper utilization of approximately one-third of the fuel charge in the initial stage of the flight. The combination of these instances substantially reduced the total impulse that could have been obtained from this ram-jet fuel charge.

## CONCLUDING REMARKS

The important results obtained in a free-flight test of a rocket-launched ram jet utilizing an end-burning solid-fuel charge are:

1. The ram jet accelerated from a Mach number of 1.90 at 3,900 feet altitude to a Mach number of 2.52 at 24,750 feet altitude in the time of 11.7 seconds.

2. The missile experienced a maximum acceleration of 3.2g during ram-jet propulsion in free flight.

3. Maximum values of net and gross thrust coefficients of 0.24 and 0.37 were calculated.

4. A maximum value of air specific impulse of 123 seconds was obtained at a Mach number of 2.45 with the free-stream stagnation temperature equal to 1020° F absolute.

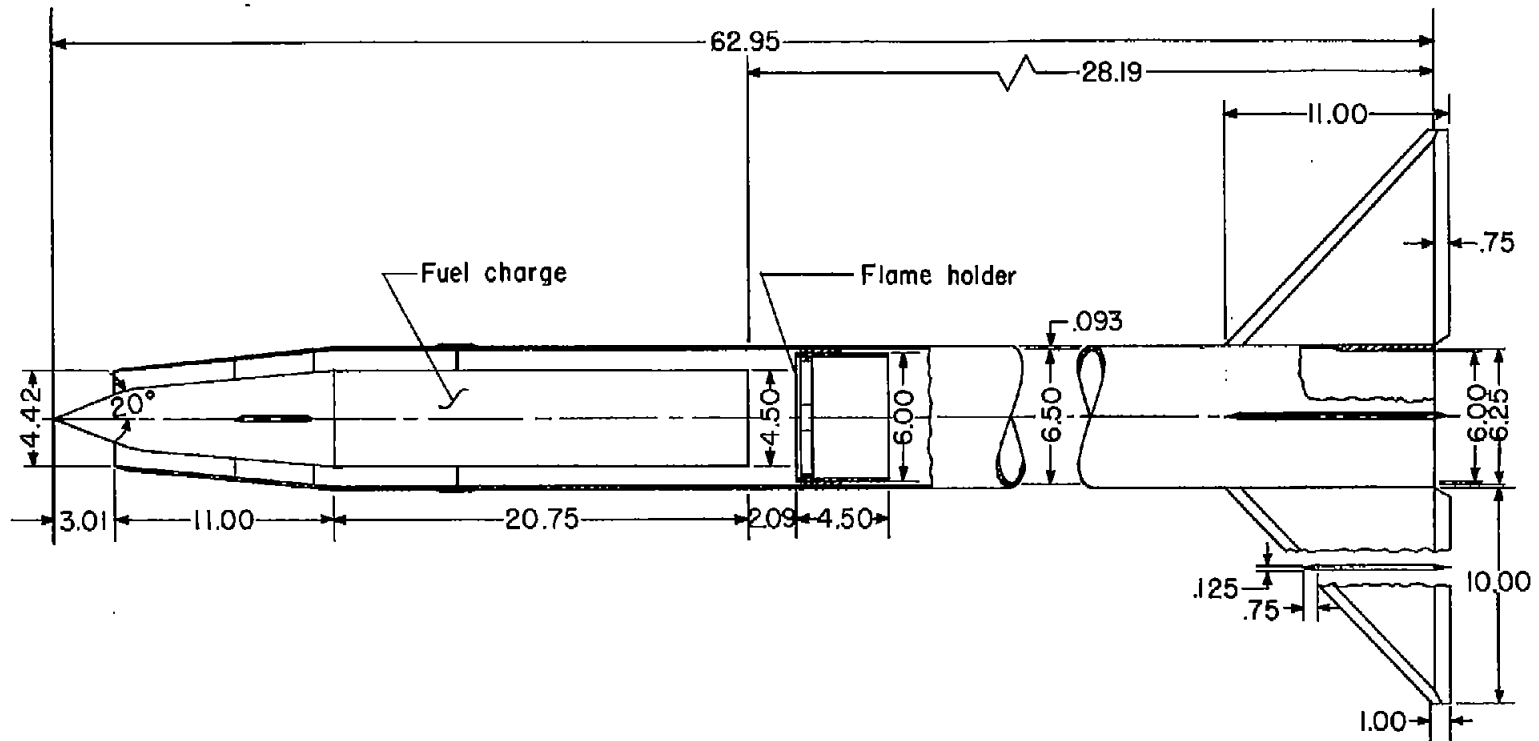
5. The fuel charge successfully withstood a maximum acceleration of 25g during the boost period.

6. The failure of the booster to separate properly penalized the performance of the ram jet.

Langley Aeronautical Laboratory,  
National Advisory Committee for Aeronautics,  
Langley Field, Va., January 25, 1954.

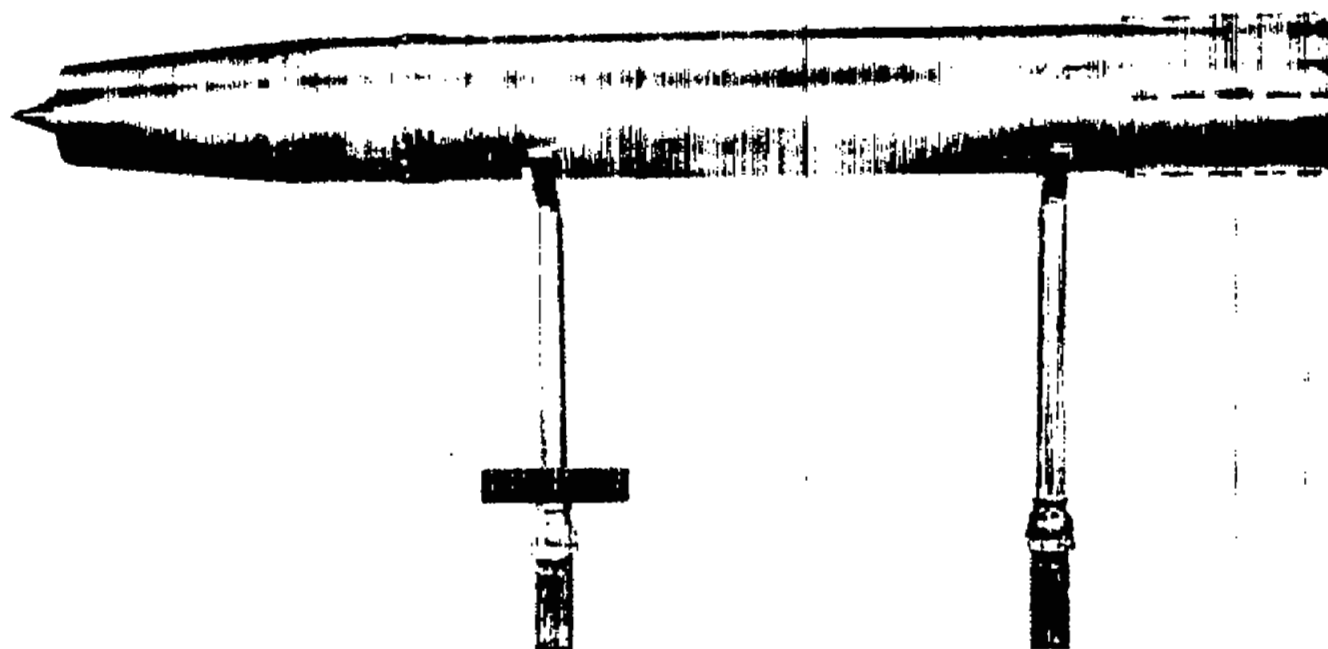
## REFERENCES

1. Bartlett, Walter A., Jr.: Evaluation of End- and Radial-Burning Solid Fuels in Ram Jets Mounted in a Free Jet at Mach Numbers of 2.0, 2.2, and 2.3. NACA RM L52I19, 1952.
2. Bartlett, Walter A., Jr., and Dettwyler, H. Rudolph: Flight Test of a Radial-Burning Solid-Fuel Ram Jet. NACA RM L52K03, 1952.
3. Herickes, Joseph A., Richardson, Paul A., and Ribovich, John: Combustion of Solid Fuels for Ram Jets. Prog. Rep. No. 24 (Proj. NAer 01206, Bur. Aero.), Bur. Mines (Pittsburgh), Jan. 1 to Mar. 31, 1952.
4. Herickes, Joseph A., Richardson, Paul A., and Ribovich, John: Combustion of Solid Fuels for Ram Jets. Prog. Rep. No. 25 (Proj. NAer 01206, Bur. Aero.), Bur. Mines (Pittsburgh), Apr. 1 to June 30, 1952.
5. Faget, Maxime A., Watson, Raymond S., and Bartlett, Walter A., Jr.: Free-Jet Tests of a 6.5-Inch-Diameter Ram-Jet Engine at Mach Numbers of 1.81 and 2.00. NACA RM L50L06, 1951.
6. Damon, Glenn H., and Herickes, Joseph A.: Combustion of Solid Fuels for Ram Jets. Prog. Rep. No. 22 (Proj. NAer 01206, Bur. Aero.), Bur. Mines (Pittsburgh), July 1 to Sept. 30, 1951.
7. Beer, A. C.: An Analytical Approach to Ramjet Design Optimization. Bumblebee Rep. No. 108, The Johns Hopkins Univ., Appl. Phys. Lab., Dec. 1949.



(a) Sketch of model. All dimensions are in inches.

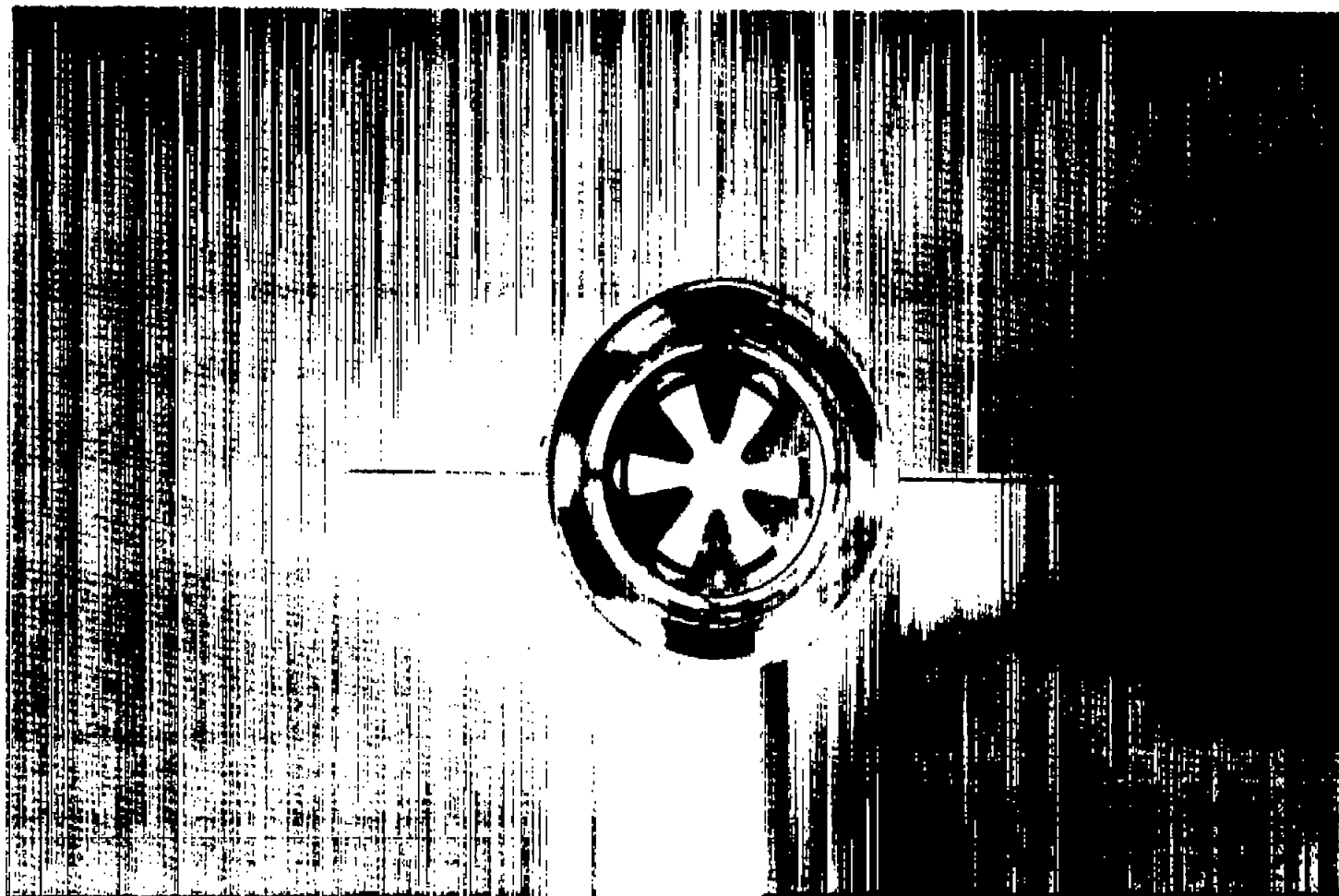
Figure 1.- The solid fuel ram jet.



(b) Photograph of model.

L-80603.1

Figure 1.- Continued.



(c) Flame-holder installation in model.

L-81000

Figure 1.- Concluded.

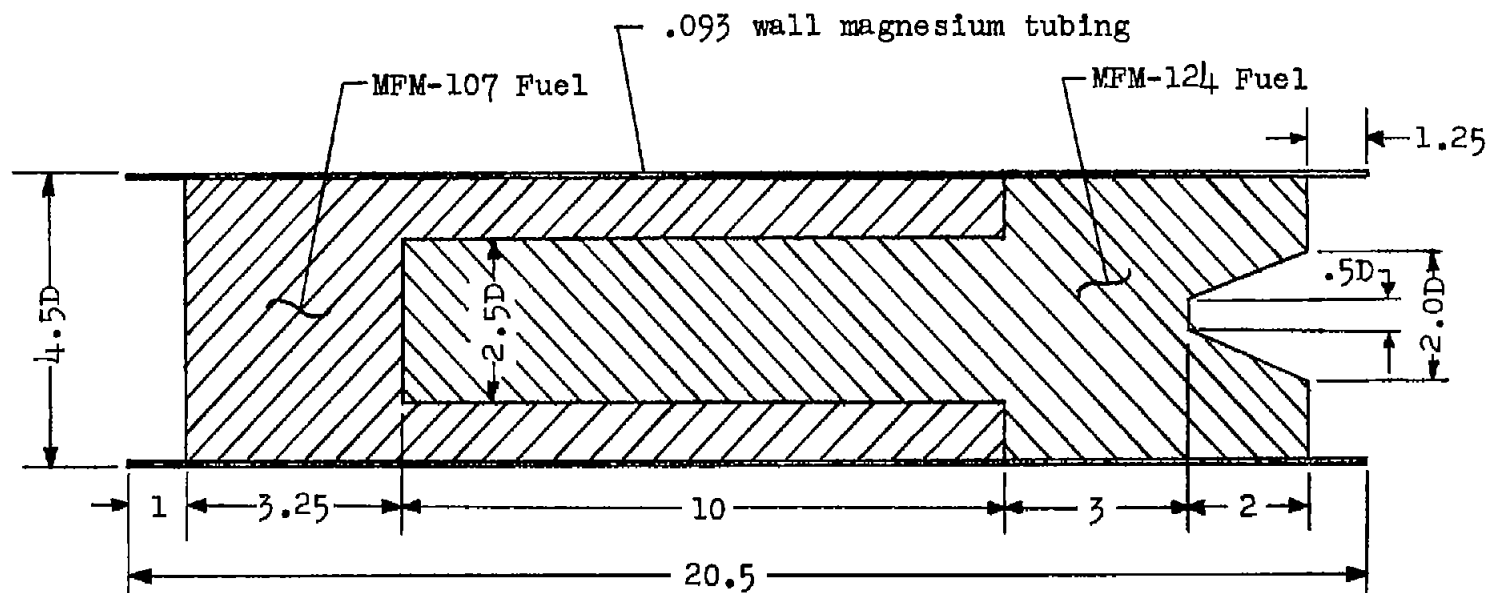
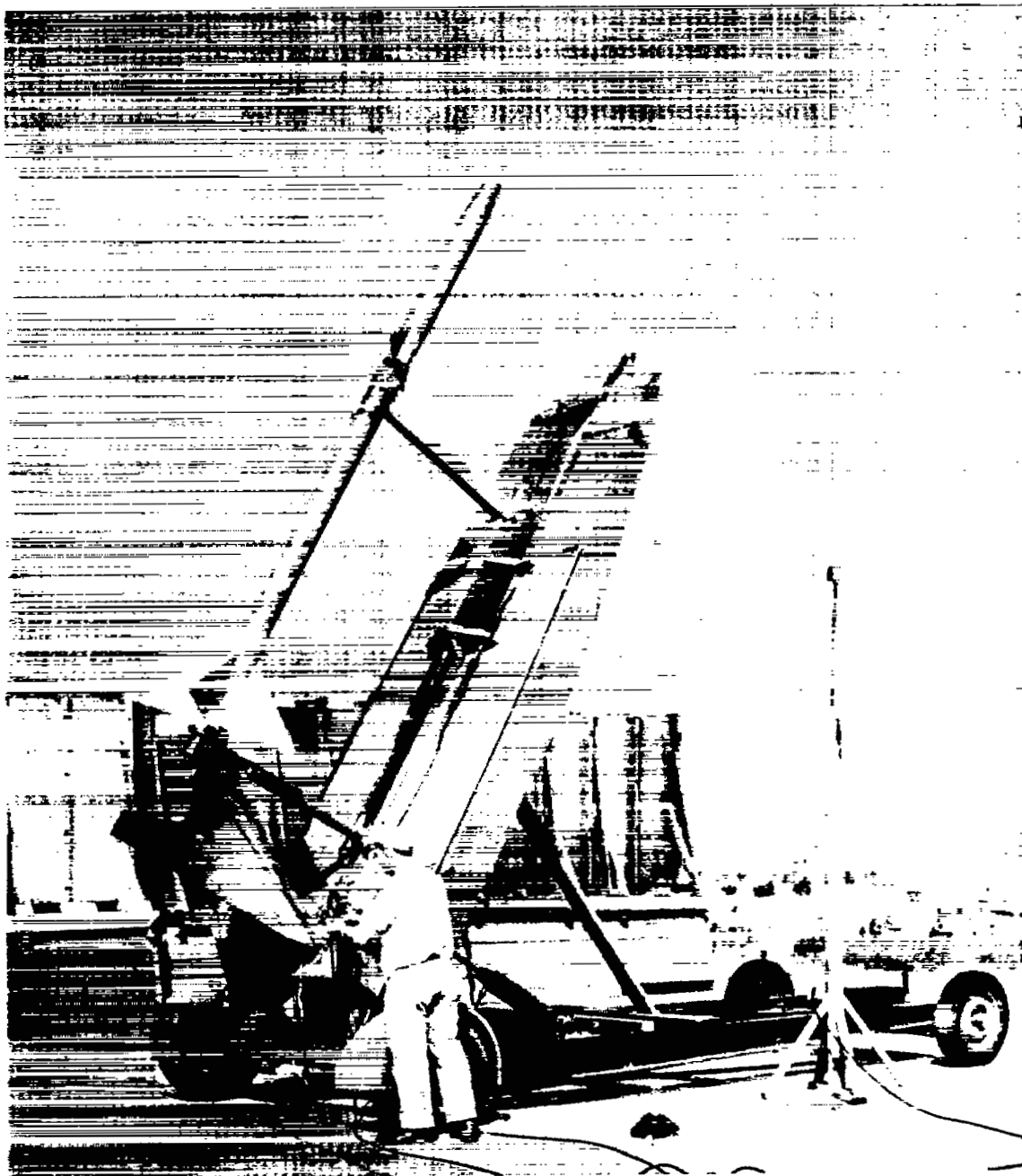


Figure 2.- Sketch of the end-burning concentric solid-fuel charge that was flight tested. All dimensions are in inches.



L-80980.1

Figure 3.- The test model and booster in the launching attitude.

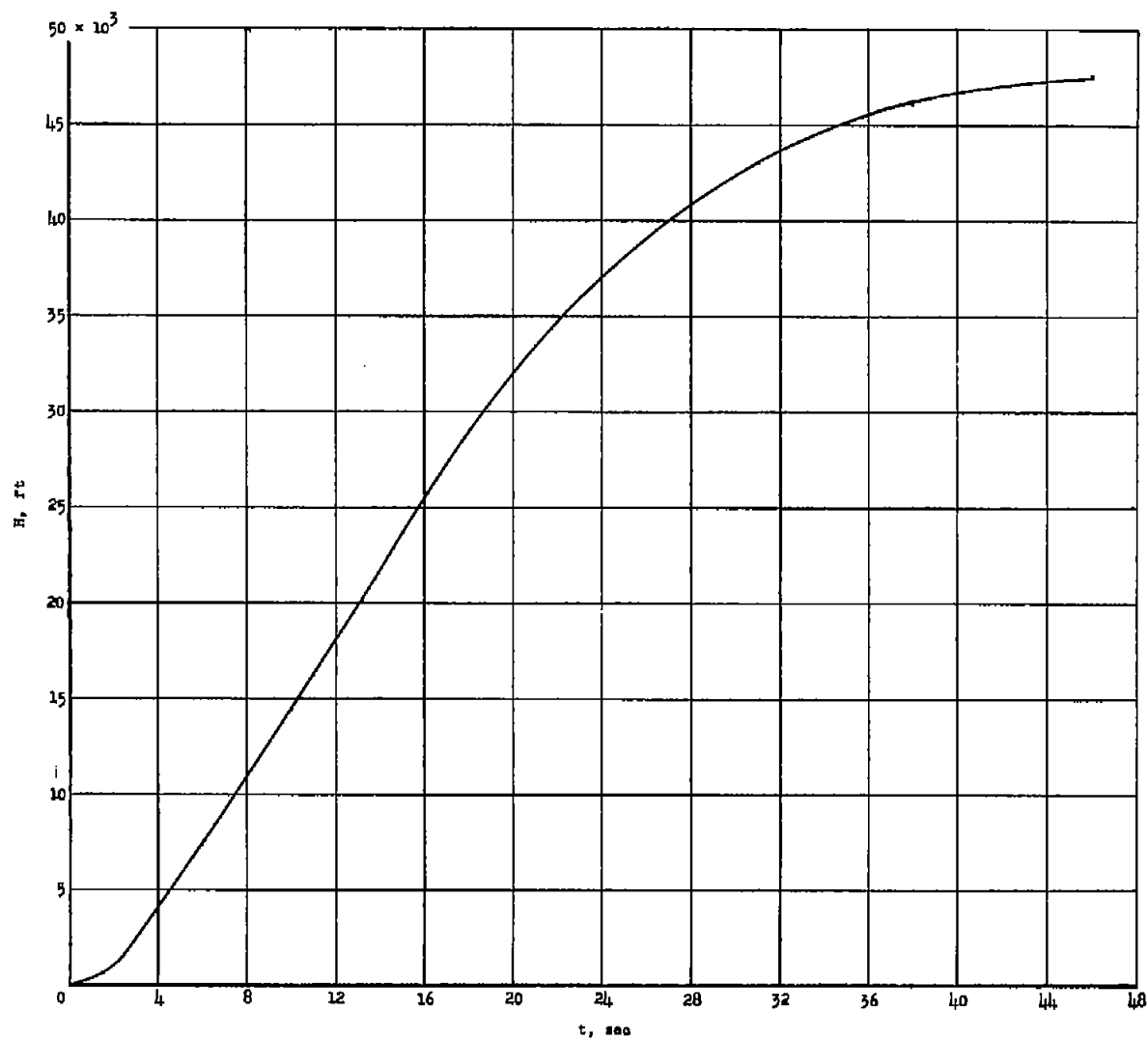


Figure 4.- The variation of altitude with flight time for the solid-fuel ram jet.

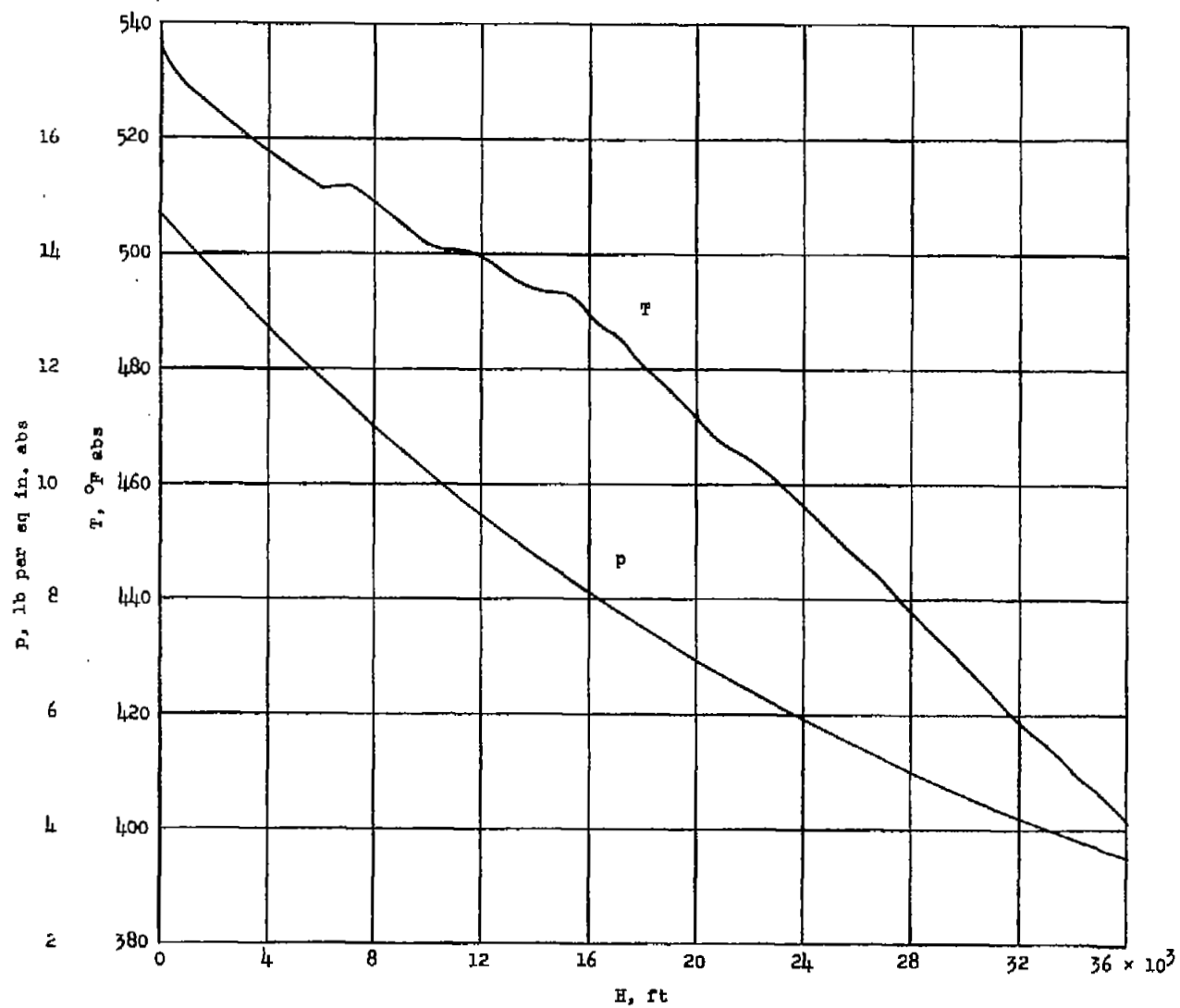


Figure 5.- The variation of ambient pressure and temperature with altitude.

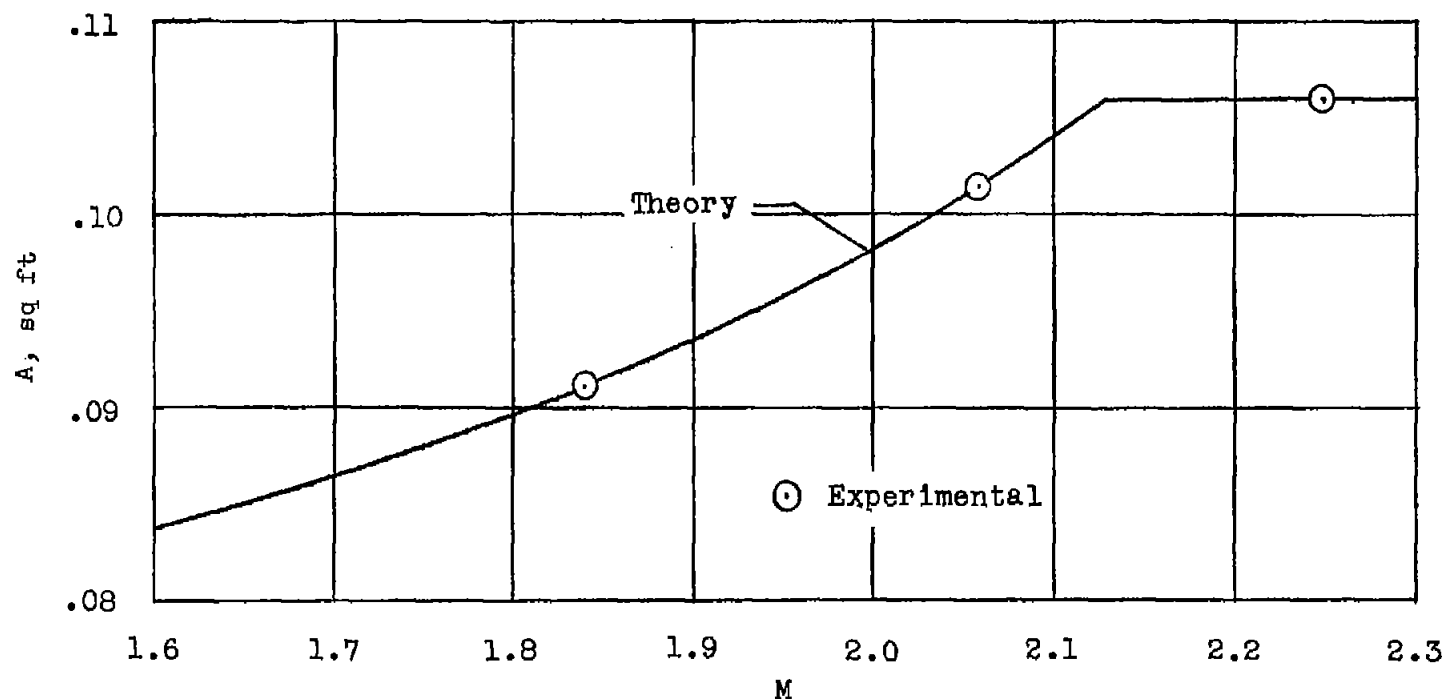


Figure 6.- The variation of maximum stream tube area with flight Mach number as determined from theory and ground tests by the methods of reference 4.

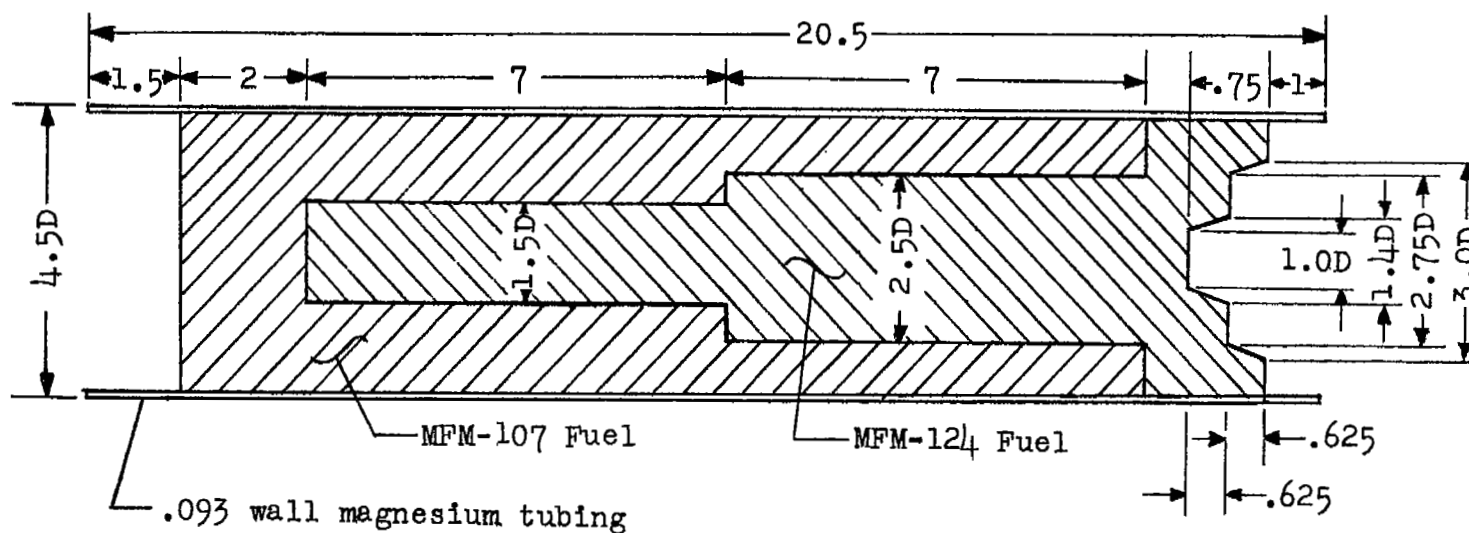
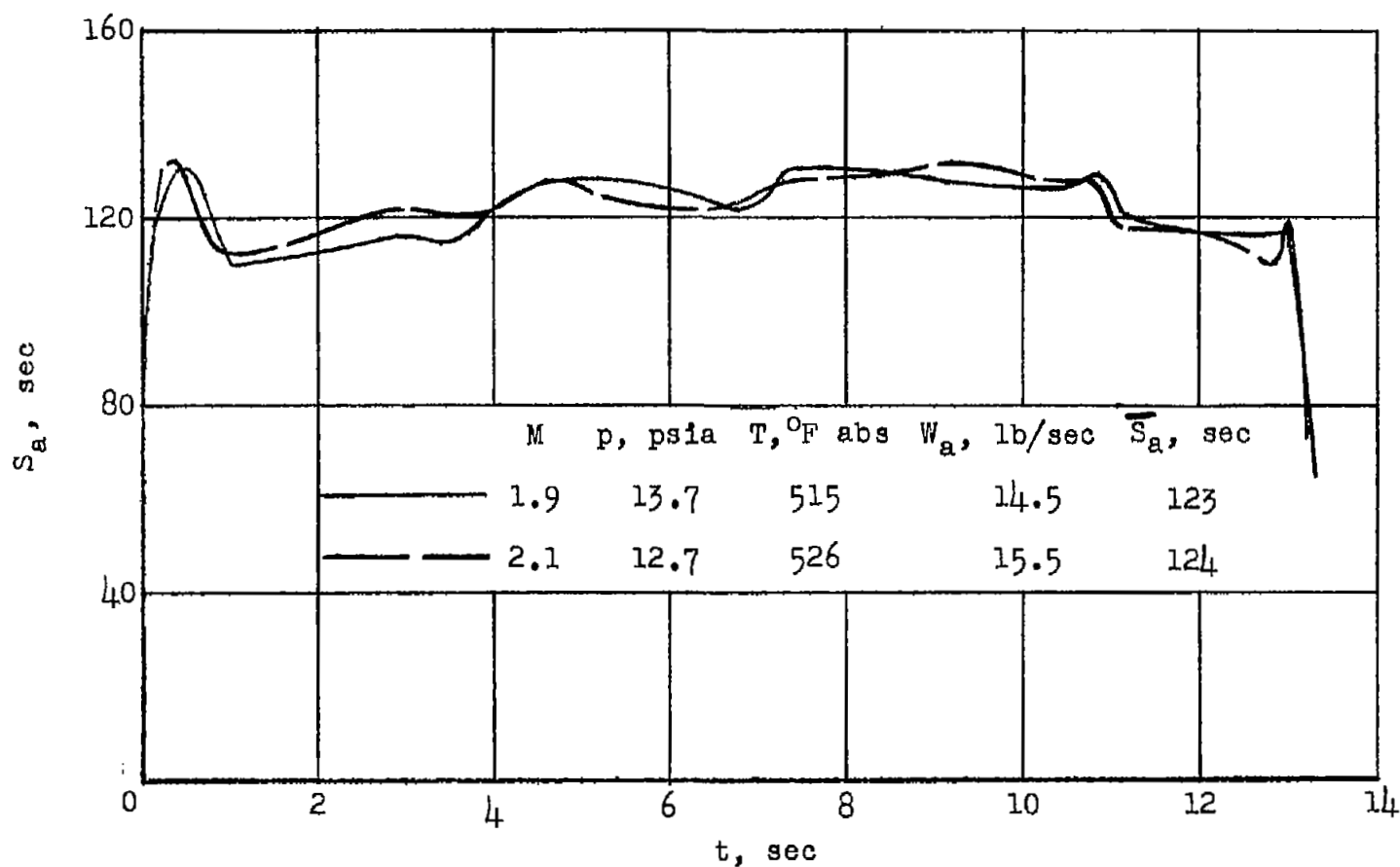
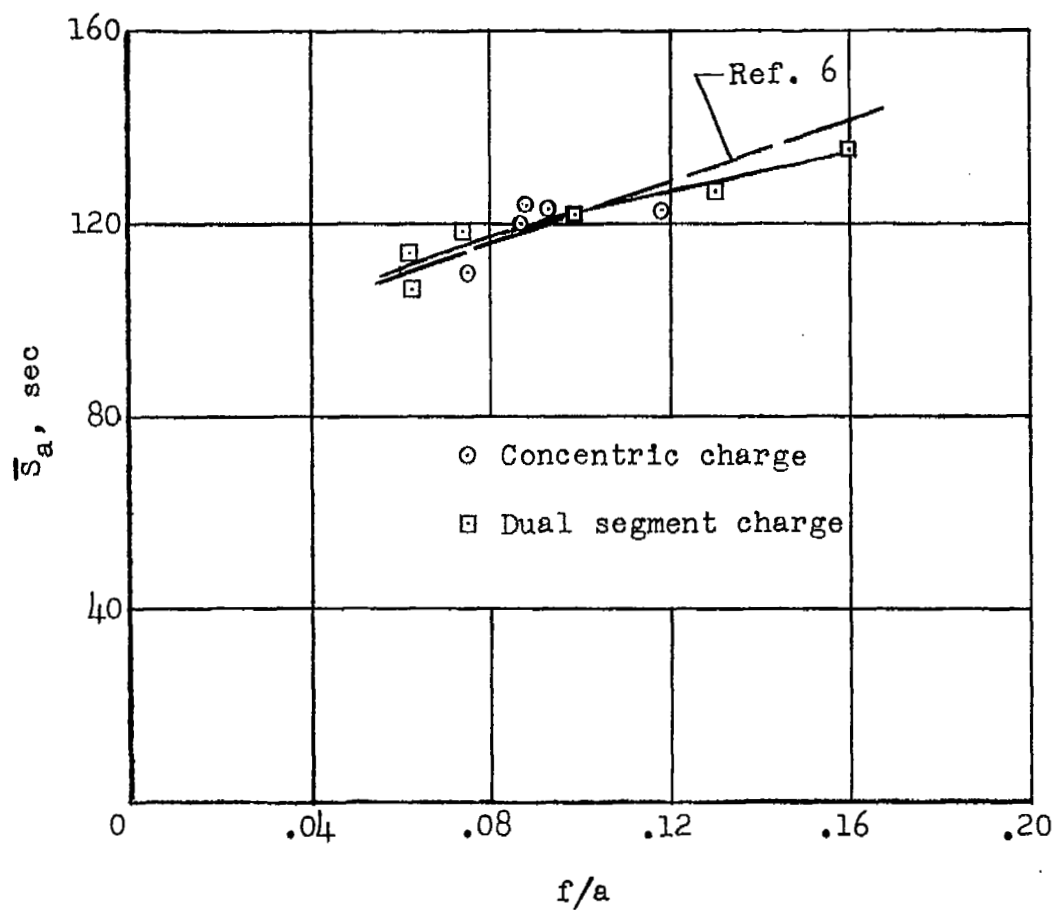


Figure 7.- The end-burning concentric-type fuel charge used in the final preflight checks. All dimensions are in inches.



(a) Time histories of air specific impulse for the concentric-type charge.

Figure 8.- Air specific impulse parameters for the fuel obtained in pre-flight jet tests.



(b) Variation of the average air specific impulse with fuel-air ratio.

Figure 8.- Concluded.

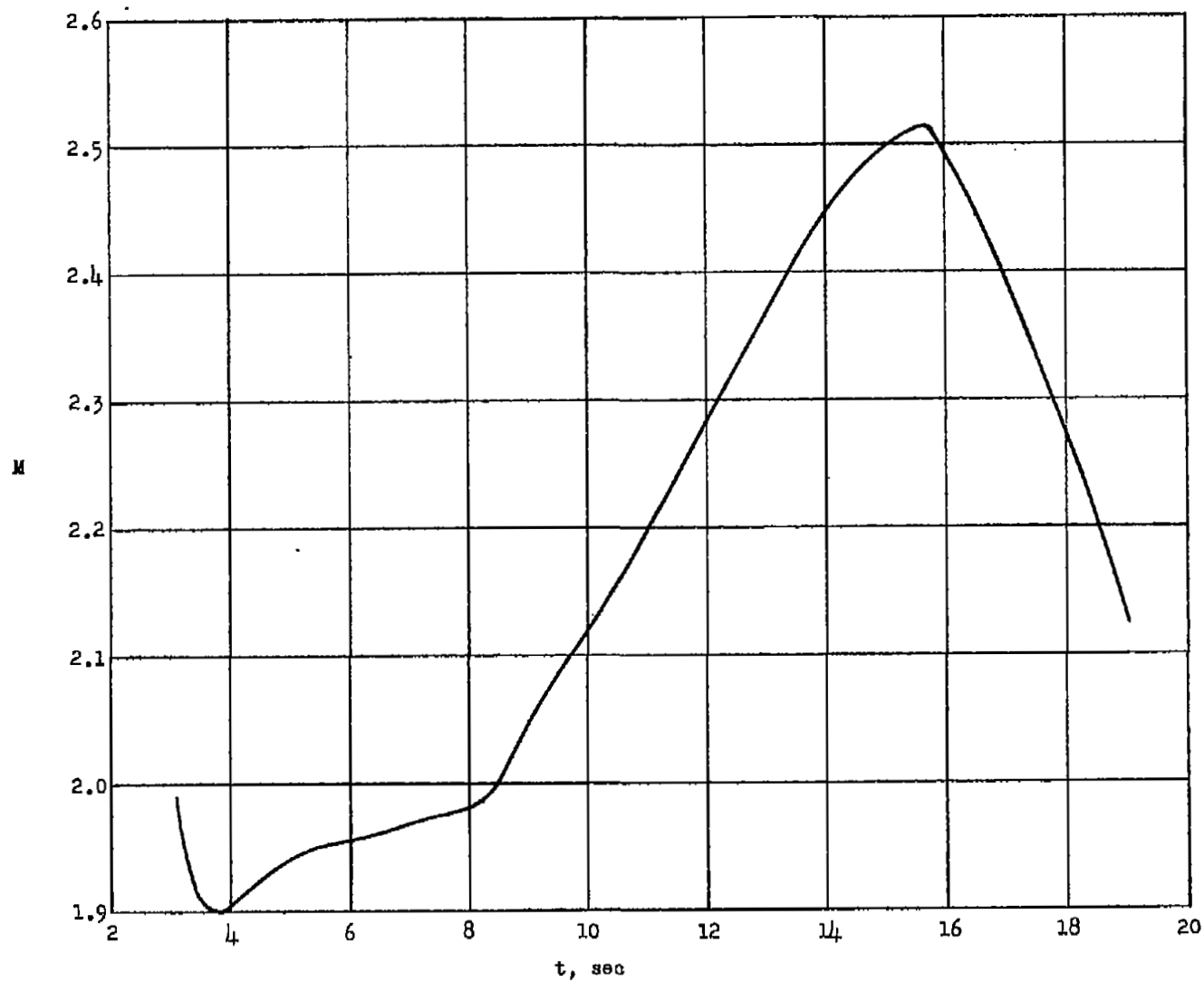


Figure 9.- The flight Mach number against time.

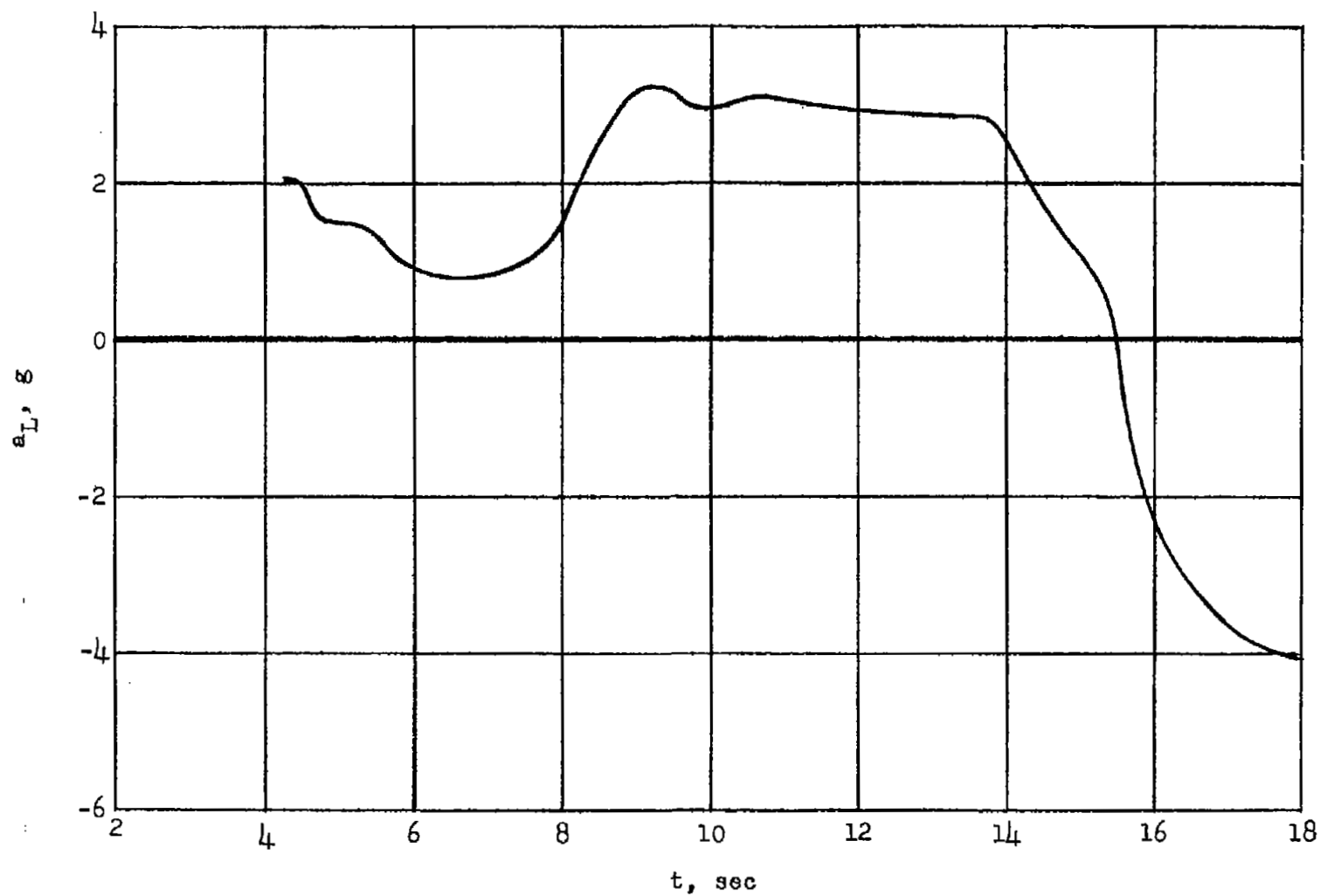


Figure 10.- The absolute longitudinal acceleration of the model against flight time.

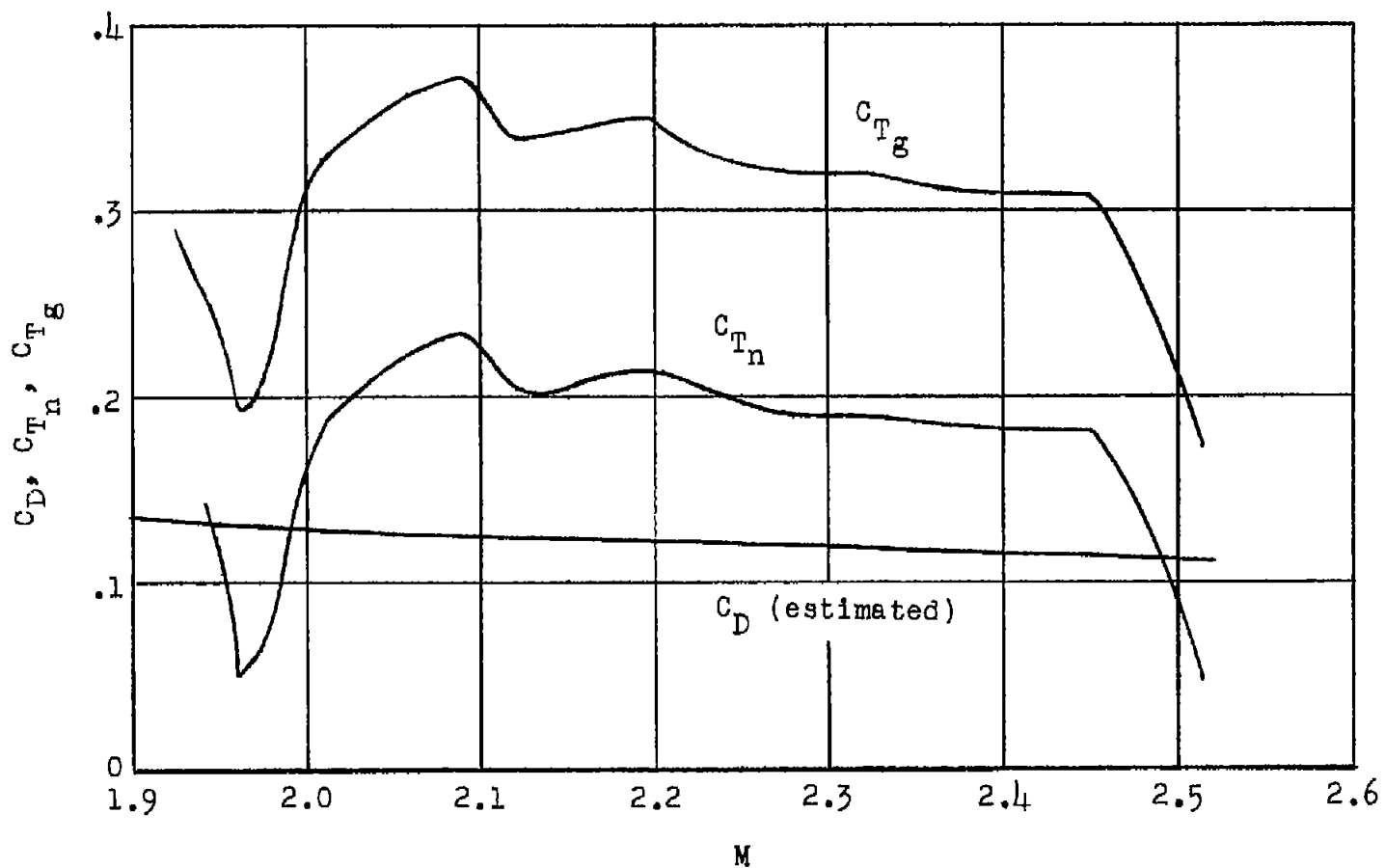


Figure 11.- The variation of thrust and drag coefficients with flight Mach number.

UNCLASSIFIED

~~CONFIDENTIAL~~

NACA RM 154B08a

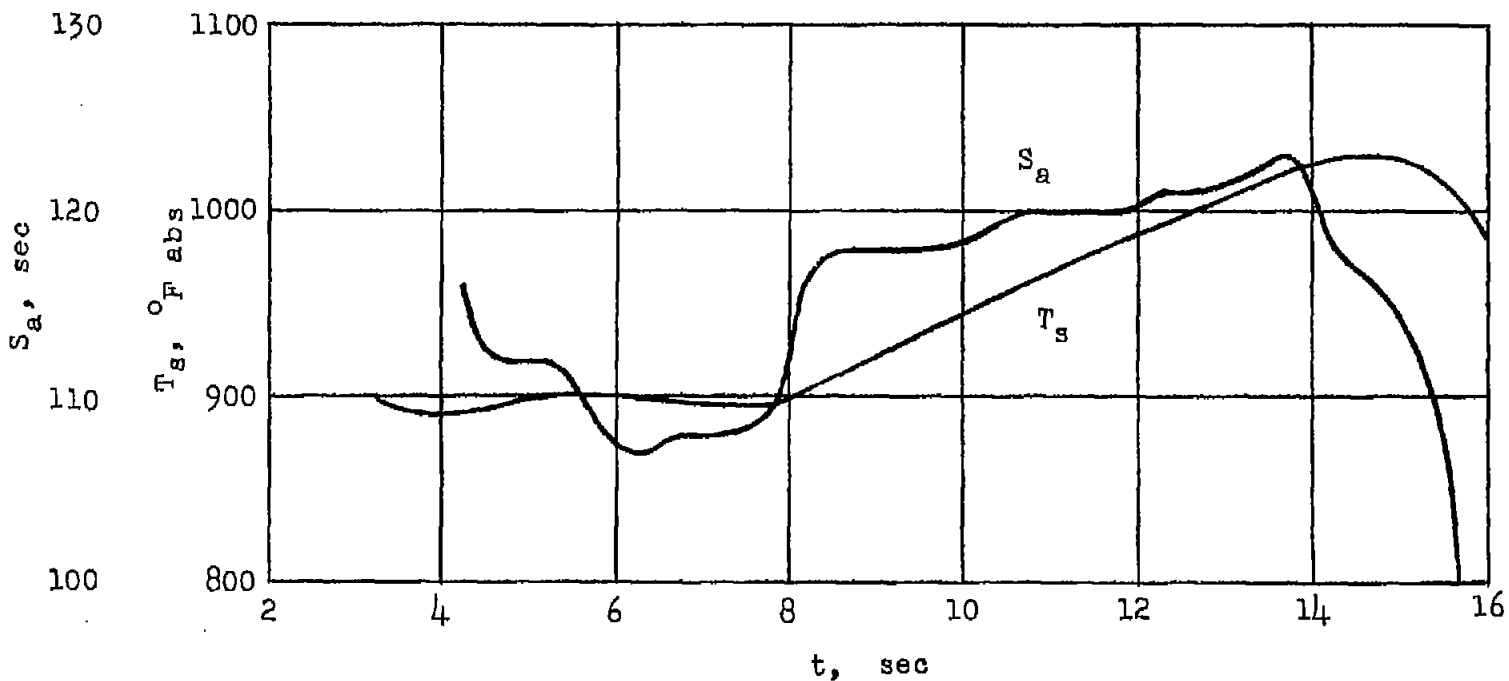


Figure 12.- The computed air specific impulse and stagnation temperature plotted against flight time.

UNCLASSIFIED

~~CONFIDENTIAL~~

NACA Langley - 3-25-44 - 324

UNCLASSIFIED

NASA Technical Library



3 1176 01437 1315

UNCLASSIFIED

~~CONFIDENTIAL~~